Subsurface Damage (SSD) Assessment in Ground Silicon Carbide (SiC)

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Abstract: We assess subsurface damage in ground Silicon Carbide, by measurement of roughness evolution and material removal rate in sub-aperture finished spots, or by estimates via material property figures of merit or abrasive size used for grinding.
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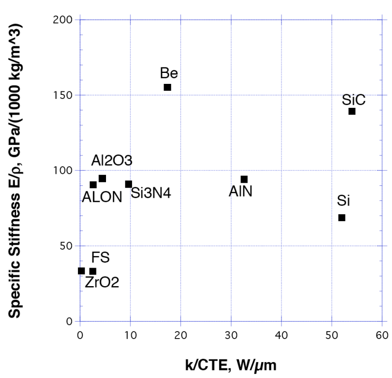
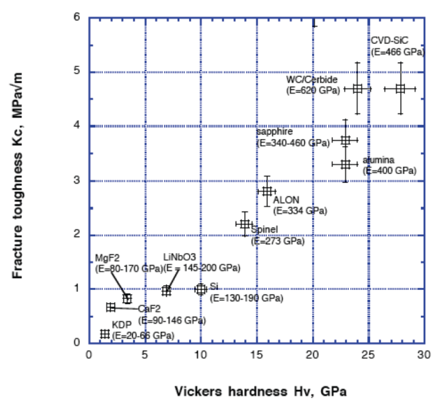
1. Introduction

Silicon Carbide is an important optical material with many potential applications in areas such as aerospace, astronomy, and lithography. The main advantage of the material arises from its high combination of mechanical and thermal stability: SiC has a very high elastic stiffness (Young's modulus E) and low mass density, allowing light weight applications. On the other hand, it has a very high thermal conductivity and a low CTE (coefficient of thermal expansion.) Therefore, it is an ideal material for lightweight mirrors, for example. Fig. 1(A) shows the thermomechanical properties of SiC in comparison with other technical ceramics and optical materials.



(A)



(B)

Fig. 1. Thermoelastic properties of SiC in relation to those of other optical ceramics and materials. (A), Specific stiffness vs. thermal stability figure of merit. Ceramics are from [1]; for ALON from [2]. Young's modulus is E, mass density is ρ, and k is the thermal conductivity. (B), Micromechanical properties: Vickers hardness Hv is for indentation loads of 200 gf, and fracture toughness Kc by microindentation.

On the other hand, machining surfaces of SiC is extremely challenging exactly because of its high mechanical stability, implying low material removal rates. This can be seen in Fig. 1(B), where the hardness and fracture toughness are correlated for a large range of materials often used in optomechanical applications: SiC has the highest combination of hardness and fracture toughness. Notice here that the only other comparable material, WC, has too high a mass density (more than 4x that of SiC) to be suitable for space applications. The extreme properties of SiC are also the fundamental reason for the difficulty in removing material by grinding, finishing, or polishing of SiC surfaces. As a result of the material removal process in SiC, for example by grinding, a subsurface damaged (SSD) layer is left in the surface. This layer contains microcracks that may compromise both the optical performance of the surface, as well as its mechanical integrity, see Fig. 2. Any such layer eventually needs to be removed by a finishing process.

We present here several approaches towards measuring or estimating the SSD zone depth in ground SiC.

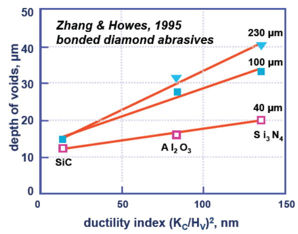


Fig. 2 Direct measurement of the damaged zone in ground ceramics, from the work by Zhang and Howes [3]. Larger abrasives lead to deeper damaged zones. SiC shows less damage than other structural ceramics. The correlation shown here is via the ductility index figure of merit [4].

2. Damage measurement via sub-aperture magnetorheological finished spots

We have shown in the past [5] that single magnetorheological spots can be used to estimate the subsurface damage of ground ceramic surfaces. Extensive discussion of how MRF single spots are used can be found in [6, 7]. Our approach here uses MRF spots of varying depths (corresponding to different dwell times), i.e. varying depths of penetration into the surface. The guiding hypothesis is that, when the spot depth penetrates below the SSD zone, the measured surface roughness stops varying with depth, attaining a (low) steady value, see Fig. 3.

A parallel hypothesis is that the material removal rate is correlated with the extent of SSD, being high when SSD is extensive and eventually attaining a low, steady value (typical of the material and the MRF finishing conditions, but independent of the SSD depth.)

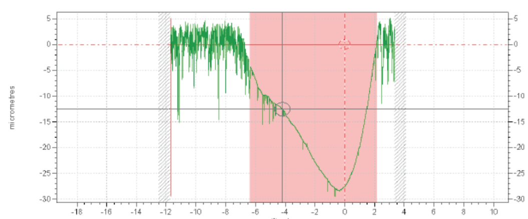
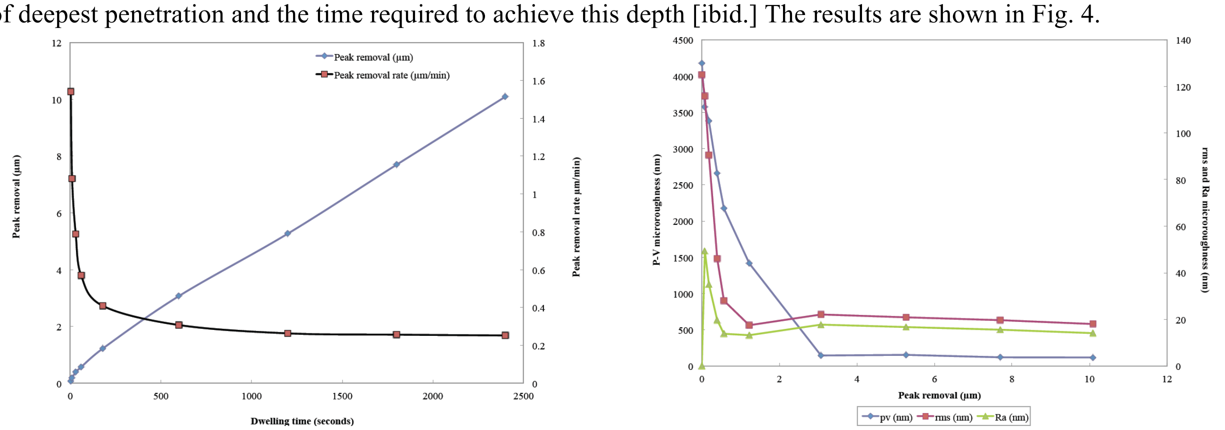


Fig. 3 Profilometer trace of a MRF single finishing spot on the surface of ground fused silica ground with alumina abrasives. When the depth of the spot (here about 30 µm) extends below the grinding-induced SSD, surface roughness is minimized. The depth of SSD is about 15 µm. The MRF spot corresponds to a dwell time of 5 min, with a 0.3 mm of depression of the part into the MRF spot.

3. Subsurface damage measurement in ground SiC

CVD SiC was ground with loose diamond abrasives (5-10 µm in size), and then finished with MRF single spots, each of different duration. Following the creation of the finished spot, the surface microroughness was measured at the spot's deepest location [7]. In addition, a maximum (peak) material removal rate was measured from the depth of deepest penetration and the time required to achieve this depth [ibid.] The results are shown in Fig. 4.



(A) (B)

Fig. 4 Measurements of surface roughness and peak removal rate in ground CVD SiC. (A), direct measurements vs. dwell time in the MRF spot. (B), correlations of surface roughness (peak-to-valley, rms, and Ra average) with the depth of the MRF spot.

4. Discussion

Our data in Fig. 4(A) demonstrate that the initial MRF material removal rate of the ground SiC surface is very high, of order 10 μm/min, and eventually settles down to a steady value of about 2 μm/min. Such a large reduction in the MRF material removal is indicative of the strong correlation between material removal rate and the state of SSD of that surface. The depth of subsurface damage can be directly ascertained from the correlation of surface roughness with the depth of material removed. The initial surface roughness of the ground surface is very high, i.e. 4 μm p-v and 120 nm rms. These features are direct consequences of the grinding process. Figure 4(B) shows that, once 1.5 to 2.0 μm of material are removed within the MRF spot, then the surface roughness settles to a steady value of about 0.15 μm p-v and 20 nm rms.

A direct consequence of these observations is also the demonstration of the state of finish of the ground SiC surface that can be accomplished by a direct application of MRF within a single spot, namely a surface microroughness of 20 nm rms.

Several hypotheses can be posed at this point in terms of, rather than directly measuring SSD, instead estimating SSD either by a material figure of merit, or the size of abrasives used in the grinding process. Fig. 2 shows that indeed this is the case in terms of the material figure of merit $(Kc/H)^2$ (units of length) approximately dictating the size of plastic deformation in a crack in the ceramic. The other correlation also can be observed from Fig. 2, namely that SSD increases with abrasive size. These observations are interpreted in terms of the upper and lower bounds of SSD that we have presented earlier, namely that [8]

$$0.3\ L^{0.68} < \mathrm{SSD}\ (\mu\mathrm{m}) < 2\ L^{0.85} \quad (1)$$

with the abrasive size L in μm. The data in Fig. 2 and in Fig. 4 conform to these bounds.

The larger research question of systematically studying SSD in ground SiC of different types and under different grinding conditions is undertaken in [9]. Research is also under way on how to effectively polish SiC surfaces by using laser polishing [10].

5. Conclusions

We have demonstrated several approaches to assess the subsurface damage in ground SiC, an important optical material. SSD can be measured by using MRF spots of varying dwell time, and hence depth. Correlation with spot depth of the peak material removal rate, and/or of the surface roughness at the deepest spot depth allows the measurement of the SSD.

Alternatively, SSD can be estimated from a material figure of merit characteristic of plastic deformation in a crack in the material, or from knowledge of the average abrasive size used in the grinding process.

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